MONITORING FLUID SYSTEM DEBRIS *VIA* DIAGNOSTIC FILTERS

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Abstract: The utility of the filter element as a diagnostic tool to augment existing diagnostic techniques for monitoring fluid system debris is discussed. Two specific ways of utilizing the filter element for the above purpose are presented:

1) The incorporation of a removable(pull-out) diagnostic layer of porous medium, in conjunction with the regular filter element medium pack, allowing for on-site inspection of the collected debris and hence, delineation of 'abnormal' fluid system component wear and/or impending component failure. The above can assist operators in preventive maintenance and 'trouble shooting', and augment existing diagnostic techniques including chip detection and spectrometric fluid analysis.

2) The on-line monitoring of the rate of contaminant loading of the filter element *via* measurement of the filter element differential pressure in conjunction with the fluid temperature and flow rate. This will assist operators in identifying 'abnormal' contaminant loading conditions that may be associated with excessive contaminant ingression or accelerated fluid system component wear once a 'normal' baseline trend for filter element differential pressure build-up in a fluid system is established. This will also assist operators in optimizing filter element service life.

It is anticipated that on-line monitoring of filter elements incorporating diagnostic layers will significantly augment existing diagnostic techniques for fluid systems.

Key Words: Diagnostics; fluid systems; component wear; debris monitoring; diagnostic filter element; diagnostic layer; on-line differential pressure monitoring; failure prediction.

Introduction: The fluid is a repository for wear debris generated by the rolling/sliding component surfaces in the fluid system, particulate contamination ingressed from the operating environment into the fluid system, and the products of fluid breakdown such as carbonaceous material resulting from the thermal break down of engine lubricants. Monitoring of the particulate contamination present in the fluid can provide valuable information about the condition of the fluid system[1] and allow for the characterization of 'normal' and 'atypical' or 'accelerated' component wear and hence, the possibility of preventive maintenance prior to component malfunction and/or system failure. Two widely utilized debris monitoring techniques are detection/evaluation of metallic/magnetic debris (chip detection) and spectrometric fluid analysis. A useful technique that augments the above diagnostic procedures is monitoring of debris collected in the filter element[2-5].

The coherent surface and 'full-flow' characteristics of filter elements are ideal for efficiently capturing particulate contamination in the fluid, including non-magnetic and non-metallic debris of interest, such as material from seals, mineral compounds that may be ingressed from the operating environment into the system, and particulates associated with fluid break down. In addition, the monitoring of the filter element differential pressure, in conjunction with fluid flow rate and temperature, provides an estimate of the particulate contaminant loading of the filter element and allows for the identification of 'abnormal' contaminant loading conditions, and prediction of impending requirement for filter element replacement[5,6], once a baseline trend has been established.

The use of filter elements with convenient diagnostic layers for monitoring fluid system debris, and filter element differential pressure monitoring as an on-line diagnostic tool, are discussed below.

Filter Elements with Diagnostic Layers: The contamination collected in filter elements is analyzed at varying levels of sophistication by many equipment operators, often to verify the results of spectrometric fluid analysis or chip detector indications, and by equipment manufacturers during 'Acceptance' testing, such as the 'Green Run' testing of aircraft engines. The use of conventional filter elements for this purpose has several drawbacks. A primary difficulty is in accessing the particles trapped within the matrix of fibers constituting the filtration media of disposable filter elements. Typically, this is time consuming and involves cutting the filter element medium pack along the circumference of the end caps, removing the pack, and separating the filtration medium from the support meshes, usually metal meshes. The process can introduce metal debris from the cutting tool as well as from the support meshes. Separating the relevant wear debris from the large background of contaminant collected on the filtration medium may also present a problem.

The above problems may be resolved by the incorporation of a removable(pull-out) layer of porous medium(diagnostic layer) in conjunction with the regular filter element medium pack. The removable diagnostic layer is pleated in with the regular filter element medium pack, above the upstream support mesh, and can be readily removed on-site for examination of collected debris, Figure 1.

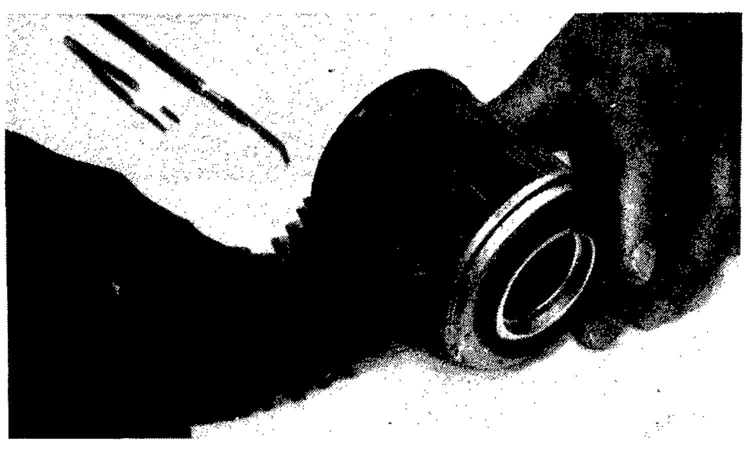


Figure 1. Filter element with removable diagnostic layer.

Important characteristics relevant to the diagnostic capability include the minimal thickness and appropriate porosity of the medium comprising the diagnostic layer. The minimal thickness ensures that the captured debris are trapped predominantly on the surface, allowing for convenient inspection, while the appropriate porosity is necessary to control the size range of particles retained on the diagnostic layer. As an example, one version of the diagnostic layer, utilized in several applications, exhibits a particle removal efficiency of ~ 95% for particles in the $\geq$ 75 µm size range, and a lower efficiency (~ 60%) in retaining debris in the $\geq$ 20 µm size range.

Filter elements with diagnostic layers have been evaluated in several bearing failure studies carried out by aircraft engine manufacturers. In these studies, the filter elements were incorporated in test stands, downstream of magnetic/metallic debris monitors. The bearings were deliberately damaged and allowed to operate to failure. The filter elements were replaced periodically, and the diagnostic layers were inspected for bearing wear debris build-up. Magnetic/metallic chip counts from the debris monitors were also recorded throughout the tests. The diagnostic layers of the filter elements, removed on 'chip indication' by the debris monitors, showed the presence of significant amounts of bearing wear debris, indicative of the onset of bearing failure. As expected, the quantity of bearing wear debris observed on the diagnostic layers, and the chip counts, increased significantly during the tests due to accelerated bearing wear prior to bearing failure, thus demonstrating the ability of the technique to augment on-board magnetic/metallic debris detectors. It should be noted that examination of the wear debris on the diagnostic layer could also provide the ability to distinguish between 'nuisance chip detector warnings' and more significant wear debris.

At present, a principal area of application of filter elements with diagnostic layers is in aircraft engine lubrication systems, both during 'Green Run' testing of engines and during regular flight operation. Numerous engine manufacturers and overhaul facilities are utilizing lubricant filter elements with diagnostic layers to examine built-in debris in engine lubrication systems during 'Green Run' testing of newly manufactured and overhauled engines. Figure 2 depicts photomicrographs of debris removed from diagnostic layers during the 'Green Run' testing of overhauled engines.

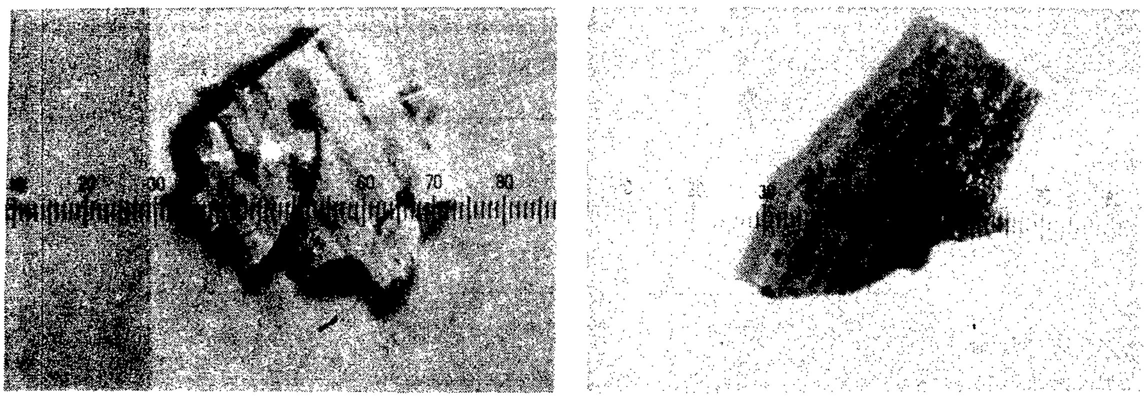


Figure 2. Photomicrographs of a titanium chip(left) and a magnesium chip(right) removed from diagnostic layers during 'Green Run' testing of overhauled engines; magnification : 50X.

Examination of the debris on the diagnostic layer during 'Acceptance/Green Run' testing can provide information about the debris built into the fluid system, during overhaul and manufacturing processes, which can contribute to accelerated component wear and failure. Characterization of the origin of the debris can provide information about the various stages in the overhaul and manufacturing processes that may contribute to built-in debris and hence, allow for process improvement.

Table I summarizes results from the evaluation of diagnostic layers during post production testing of two aircraft engines, designated Engine #1 and Engine # 2, at an engine manufacturer's test facilities. Filter elements with diagnostic layers were utilized in place of the standard lubricant filter element in the engine as well as in the test stand, downstream of the engine, corresponding to the lubrication system scavenge section. Based on the standard criteria employed by the engine manufacturer, it was determined from the visual observation of the diagnostic layers that the diagnostic layers corresponding to the test stand filter elements were heavily contaminated. The diagnostic layers corresponding to the engine filter elements were not as contaminated due to the fact that the engine filter is located downstream of the test stand filter. The mass of contaminant collected on the diagnostic layers and the chemical elemental composition of the contaminant are summarized in Table I. The results confirm the conclusions of the visual examination of the diagnostic layer, with the mass of contaminant collected on the diagnostic layers corresponding to the test stand filter elements being significantly higher than the mass of contaminant collected on the diagnostic layers corresponding to the engine filter elements. Further, the chemical elemental composition of the contamination proved to be of value in determining the origin of the contaminant. The above illustrates the utility of the diagnostic layer during 'Acceptance/Green Run' testing.

Table I. Evaluation of contamination collected on diagnostic layers of lubricant filter elements during post production testing of aircraft engines.

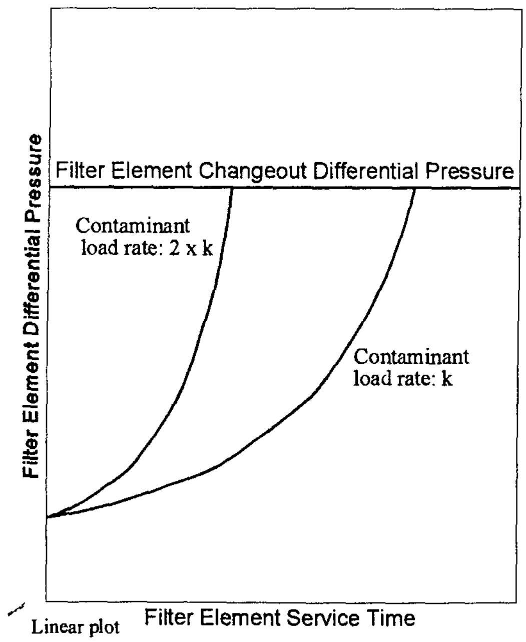
Engine #	**Filter Location**	**Contaminant Weight(mg)**	**Chemical Elemental Composition[1] (XES Analysis)**
Engine # 1	Engine (primary)	4.8	Major: Si, Cl Moderate: Al, Ag
	Test Stand (scavenge)	36.7	Major: Si, Ag Moderate: Fe, Ti, S
Engine # 2	Engine (primary)	2.6	Major: Si, Cl Moderate: Fe
	Test Stand (scavenge)	39.1	Major: Si Moderate: Fe, Ag

[1] Al = Aluminum; Ag = silver; Cl = chlorine; Fe = iron; S = sulfur; Si = silicon; Ti = titanium

The wear debris collected on the diagnostic layer can also provide valuable information about component wear during regular fluid system operation. Once a baseline is established, the presence of 'abnormal' debris can signal component malfunction and/or impending component failure. Lubricant filter elements with diagnostic layers are currently utilized in one series of engines, during regular flight operation, by a major airline in North America; over 1.5 million hours of flight service have been accrued to date. Experience with the diagnostic layer has been positive, and specific protocols and baseline trends have been developed by the airline to characterize debris collected on the diagnostic layer, and to take appropriate maintenance actions. In several reported instances, corrective maintenance actions, based on the evaluation of the contaminant on the diagnostic layer, have resulted in avoiding delays/in-flight engine shutdowns.

Filter Element Differential Pressure Monitoring: Since the differential pressure across a filter element is a function of the fluid flow rate, viscosity(temperature), and the contaminant loading, monitoring of the filter element differential pressure, in conjunction with information about the fluid temperature and flow rate, can provide information about the contaminant loading(load rate) of the filter element.

Figure 3 illustrates typical curves of filter element differential pressure build-up with service time, based on accelerated contaminant loading tests in the laboratory at constant fluid temperature and



Note: Constant fluid flow rate and temperature

Figure 3. Typical curves of filter element differential pressure build-up *vs* service time.

flow rate, for a baseline contaminant load rate designated k(mass/time) and for a contaminant load rate corresponding to twice the baseline load rate(2 x k). In Figure 4, the first derivatives of the pressure build-up curves in Figure 3 are plotted to illustrate the rate of change of filter element differential pressure for the two contaminant load rates. As expected, the curve corresponding to the

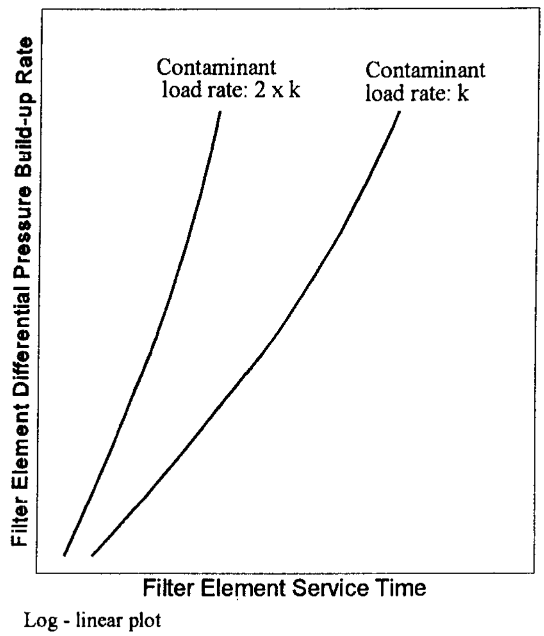


Figure 4. Filter element differential pressure build-up rate *vs* service time.

higher contaminant load rate(2 x k) exhibits a steeper slope. Thus, on-line monitoring of the filter element differential pressure build-up rate, under 'rated' fluid flow and temperature conditions, would allow for the identification of 'abnormal' contaminant loading conditions that may arise due to accelerated component wear, excessive contaminant ingression from the environment, or particulates associated with fluid break down, once a baseline trend has been established. The use of a filter element with a diagnostic layer would also permit operators to examine/identify the contaminant on-site in the event that 'abnormal' contaminant loading conditions are detected. In conjunction with other diagnostic information, this can assist in the identification of accelerated fluid system component wear and hence, allow for preventive maintenance.

The development of the technology for on-line monitoring of filter element differential pressure is at the 'Proof of Concept' stage. An electronic sensor, designed to measure filter element differential pressure and temperature, has been developed. It is comprised of a fused strain gauge circuit in a piezoresistive differential pressure transducer, and a precision thermocouple to measure temperature. The sensor provides continuous differential pressure and temperature output signals(analog or digital) and can be interfaced with electronic control systems such as the ECU or FADEC systems in aircraft engines. A flow sensor may be incorporated, if required, or flow rate information obtained by other means could be interfaced with the control system.

In addition to identifying 'abnormal' contaminant loading conditions, the sensor can also assist operators in optimizing filter element service life. Consequently, sufficient advance warning of impending filter element by-pass will be provided, allowing operators to take appropriate measures to prevent filter element by-pass.

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